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ELECTROWETTING-BASED DRIVING OF LIQUID-METAL DROPLET FOR RELIABLE RF SWITCHING

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Final Report

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This report has been approved for publication.

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Project Manager

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14. ABSTRACT

The basic idea of electrowetting-based driving of liquid-metal droplets at microscale is proven, using microfabricated prototypes. A detailed theory of our actuation mechanism is developed, and various experiments were performed to validate the theory and techniques developed to overcome the interface-charging problem. Based on the theoretical understanding, new devices are designed for integration with microwave circuits and actuation speeds better than 3.3 cm/s are demonstrated. Pursuing reduction of hysteresis for achieving high actuation speeds would be a good future topic beyond the current project. In the mean time, characterization of liquid-metal for high RF frequencies is performed experimentally, using a stationary (i.e., not actuated) mercury droplet in a RF electrode pattern designed for this testing purpose. Better than -25 dB isolation is provided. New devices are designed and simulated using HFSS to significantly lower the insertion loss. Based on the new design, devices are fabricated and measured results showed less than 0.15 dB insertion loss. The knowledge gained and results obtained in the project point to the liquid-metal droplet switch designs that can be fabricated and tested for RF performance.

15. SUBJECT TERMS
Electrowetting; Droplet switch; Liquid-metal switch; RF microswitch

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A. Summary

Goal, Approach, and Significance

The goal of this project was to develop new mechanisms of driving liquid-metal (LM) droplets and apply it to design reliable RF switch devices. We aimed to demonstrate two different actuation schemes. The first one, adapted from the proven continuous electrowetting (CEW), thin-electrolyte continuous electrowetting (TECEW) works even when the channel is not filled with electrolyte. By filling the channel with an insulating fluid (e.g., oil or air) instead, TECEW allows for both a very good capacitive coupling across a very thin solid dielectric layer and an excellent isolation across a thick fluid dielectric layer, while keeping the low-voltage, low-power consumption nature of CEW. The second mechanism mimics a comb-drive actuator in liquid phase by using the fringing fields to drive the liquid metal. Pure electrostatic drive of liquid-metal droplets has already been demonstrated but with a limitation of maximum displacement. This mechanism, using a mix of electrostatic and electrowetting forces, allows for a large displacement of liquid-metal droplet in air. Absence of even the thin layer of electrolyte will offer even better RF performance. Solid-solid contact, considered the primary source of reliability problem in most of RF MEMS components, is completely eliminated. The resulting switch is expected to provide excellent RF performance and reliability and operated with low voltage and low power consumption.

Accomplishments

In the first 6 months we were able to demonstrate TECEW phenomenon at microscale. Formation of thin liquid films in channels and subsequent assembly with liquid-metal droplet was studied. This helped in development of the device design. Device prototypes were fabricated on silicon and glass substrates and were successfully actuated. In order to gain a better insight of the device physics we developed a detailed theoretical model of the system.

Having already demonstrated devices based on TECEW phenomenon at microscale our objective was to concentrate on the development and demonstration of devices based on electrostatic actuation. Prototype devices for electrostatic actuation were demonstrated. Theoretical investigations lead to development of a model, which was validated by experiments. Based on the initial experimental understanding of the phenomenon we designed devices, with the intent of integrating it with microwave circuits, for development of a switch. These devices were tested separately (independent of the microwave circuits) and achieved driving speeds better than of 3.3 cm/s and actuation voltages as low as 80V. Future research will focus on improvement of switching times by reduction of actuation gap and increasing the actuation speed.

Characterization of liquid-metal performance for high RF frequencies was also pursued. Simple microwave circuits were designed and liquid-metal switch was characterized under simulated conditions. Measured performance showed better than -25dB isolation. Experimental results were matched to simulated results using HFSS software. New device designs were simulated to optimize RF performance. Based on the simulations we fabricated new devices for better RF performance. Measured insertion loss for these improved designs was better than 0.15dB up to 40GHz. Future work will involve electrothermal analysis of the device to investigate high power capabilities of the switch.

B. Project Description

Because the reliability problems of most RF MEMS components originate from the solid-to-solid contact, many consider the use of liquid metal (LM) as a solution. Microdevices using LM droplets have been pioneered by the P.I. of this project [1-5]. The first MEMS switch that incorporated microscale mercury drop in its microfabrication was based on thermal expansion of a filling liquid to switch the mercury droplet for microrelay applications [1]. A more recent approach is for electrostatic switching of a mercury droplet for low operation power requirement, [5]. Despite the successful LM-based MEMS devices in applications including relays, there has been no design or technology suitable for RF switches. Continuous electrowetting (CEW) mechanism, despite its superior characteristics for driving microscale LM droplets [3], did not bring the success for RF applications, in short because of the lossy nature of the electrolyte at high frequency (GHz) range [6]. In this project, we strive to overcome the main obstacle that has been discouraging the use of CEW for RF applications.

We propose a new type of RF microswitches, whose concept is schematically illustrated in Figure 1. Actuated by the newly invented Thin-Electrolyte Continuous ElectroWetting (TECEW) mechanism, which allows driving of a LM droplet (e.g., mercury, gallium, or low-melting-temperature metals) in a microchannel filled with a dielectric fluid (e.g., air, oil [7], etc.), the device has RF signal electrodes turned "on" when connected by LM and turned "off" when separated by the dielectric fluid.

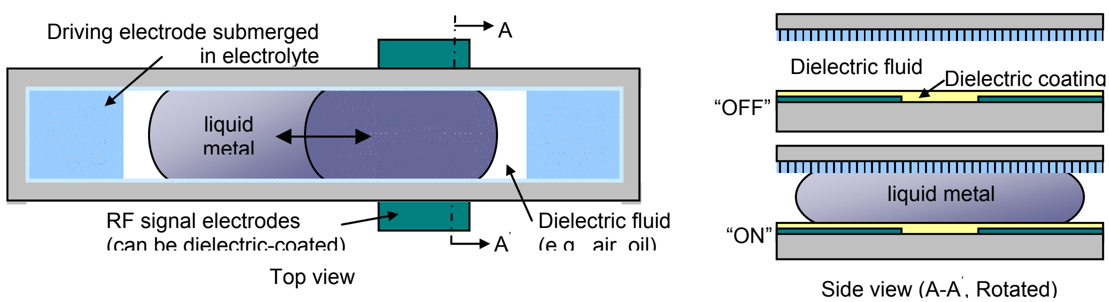


Figure 1. Working principle of TECEW-based RF MEMS devices (not to scale)

The proposed LM-based RF components are expected to bring out the much needed characteristics summarized below:

- Absence of moving mechanical parts means no friction, no wear, no surface degradation and no fatigue in device during operation.
- Unlike conventional switches with solid–solid interfaces, liquid–solid interface provides inherently superior contact reliability and is free of even 'in-use' stiction. It would not suffer from 'contact–bounce' or surface degradation, unlike other MEMS switch using solid contacts.
- TECEW enjoys the same advantages of CEW -- very low driving voltages (1-4 V) and ultra low power (μW's) [3].
- Driving voltage requirement is independent of RF electrode gap, which is not true for other MEMS RF switches. Thus, ultra high isolation is achievable with the same low driving

voltages. Large electrode gaps (200 µm or more) with an isolation medium ensure very high isolation (30dB for air) even at high RF frequencies.

- Even at very high frequencies (15 GHz), mercury has been reported to show very low insertion loss, which is comparable to copper through-connect [6].
- Latching switch can be achieved without adding latching mechanism in the switch.

Though CEW has been studied in some detail before, the TECEW phenomenon was investigated in this project for the first time. Formation of thin films is not a natural process. Understanding the theory of thin films is important for successful formation of stable electrolyte films. Different electrolyte–dielectric pair and/or micro/nano-structured surfaces were considered as suitable mechanisms for formation of thin films. The goal was to determine how the stability of the thin films depends on different electrolyte–dielectric combination, physical device properties, driving voltage and external factors (evaporation). TECEW characterization included the study of actuation velocity dependence on driving voltage under varying operating conditions. Faster actuation velocities, and hence shorter switching times, can be achieved with higher driving voltages. However, the maximum applicable driving potential is determined by the onset of electrolytic dissociation of the electrolyte.

Concerns about high frequency performance of the device in the presence of thin electrolyte lead us to seek an electrolyte-less driving mechanism of the liquid-metal for switching as shown in Figure 2. Developed on electrostatic actuation, the mechanism tries to mimic comb-drive actuators in liquid phase by using fringing fields to actuate liquid metal droplets. Unique nature of the drive takes advantage from a mix of electrostatic and electrowetting phenomenon for microactuation. This mechanism will be further developed to assess its performance under high frequency and high-power applications. Electrostatic actuation based switch is not only expected to have all the benefits of the previous mechanism but, will outperform the TECEW scheme in RF performance due to absence of leakage paths through the thin layer of electrolyte. Absence of electrolyte will also allow a better thermal operating range.

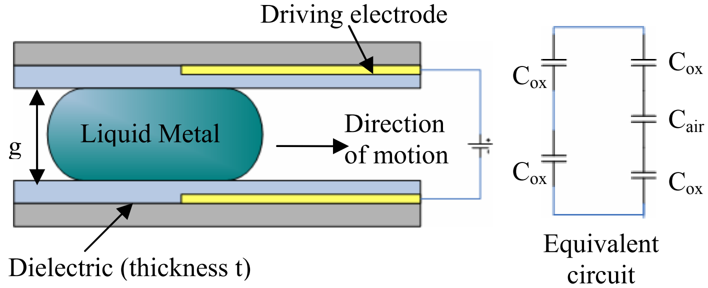


Figure 2. Schematic of electrostatic based actuation of liquid-metal droplets

For liquids, presence of charged species at the interface leads to a change in surface tension which causes a change in the contact angle. This phenomenon is called electrowetting. To understand the contribution of both the phenomenon's, electrostatic and electrowetting, a theoretical investigation and experimental validation was required. Driving voltage depends on the dielectric properties and the surface quality. Higher dielectric constant and smaller dielectric thickness results in lower driving voltages. However, the minimum dielectric thickness is determined by the onset of dielectric leakage (breakdown). Surface modification, chemical (i.e.

surface coatings) or physical (i.e. structured surface), will reduce hysteresis and improve actuation speed.

Theoretical study of the mechanisms guided the design of initial devices. Our objective was to understand the limitations on device configurations such as channel shape and size, electrode installation, substrates used, etc. We also established a basic understanding of performance of the devices. Absence of moving mechanical parts allowed us to test a variety of designs on a wide array of substrates. Future work will involve development of microfabrication techniques to make RF switches using different designs and on different substrates. Packaging will be critical for prolonged life and efficient functioning of the device. The technology will have to take into consideration the insertion and subsequent presence of multiple fluids (dielectric, electrolyte). Microgasketing will be the initial choice for micro packaging. Eventually however, other packaging techniques will be developed for better device reliability.

C. Accomplishment

Task #1: Process Development and Device Fabrication

We accomplished our primary objective for the first half year by demonstrating TECEW at microscale. Several device structures and substrates were used in fabricating and testing prototypes. Primary requirement for developing a TECEW device is formation of a stable thin electrolyte film, which is hindered by surface tension, finite contact angle and evaporation of the thin film. Microgasketing, a room temperature bonding technique for microfluidic devices developed previously in our lab, was used to successfully seal the devices and reduce the evaporation related problem.

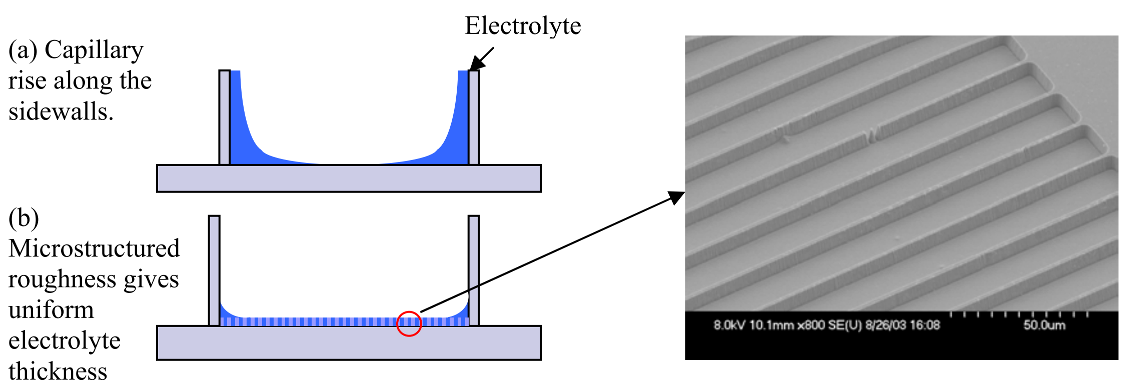
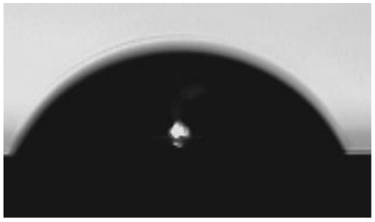
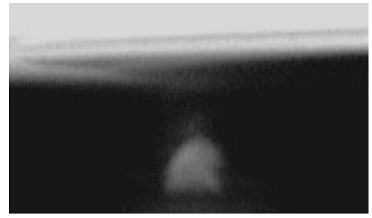


Figure 3. Microstructured rough surface to increase wetting uniformity

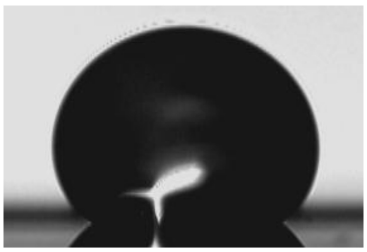
Surface tension leads to capillary rise along the sidewalls of the enclosing channel. As illustrated in Fig 3(a), this concentrates most of the electrolyte to the sidewalls with no electrolyte at the center of the channel and thus restricting motion. Surface roughing is known to increase hydrophobicity and hydrophilicity of surfaces. We realized the use of microstructured rough surfaces in breaking the liquid continuity and capturing the liquid in small microchannels to improve the electrolyte uniformity in the channel, as shown in Fig 3(b). Though microstructured surfaces increased the uniformity of the liquid layer, addition of surfactant to the electrolyte was required to achieve a thin layer of electrolyte, as observed in Fig. 4.



DI Water on flat surface (56 degrees)



DI water with surfactant on flat surface (20 degrees)



DI water on line pattern (130 degrees)

DI water with surfactant on line pattern – spreads uniformly – not measurable

Figure 4. Effect of line pattern and surfactant on wetting profile

Devices were designed and fabricated on silicon and glass substrates. Actuation was demonstrated on all the devices with varying actuation speeds. But overall actuation speeds were significantly lower than expected. To investigate the reasons for decreased actuation speeds we performed a detailed theoretical study of the phenomenon. Electrokinetic flow of liquid-metal droplets in bulk fluid has been studied, theoretically and experimentally, for a long time. But, theoretical explanation for liquid-metal in an electrolyte filled channel was not present. We developed a detail theoretical model for the system. Surface tension is uniquely determined at an individual point by the local electrostatic potential, which is in turn given by the electric field distribution in the electrolyte. Electrostatic potential variation at the liquid-liquid interface generates a normal surface tension difference and a tangential surface tension gradient, which accounts for the driving force. Navier-Stokes equation is used to describe the flow field of both the liquids with proper inclusion of the forces acting on the electric double layer. Electrostatic potential distribution is solved using Poisson's equation and current continuity equation. Analytical solution of the model is not possible. Numerical solution has been postponed as future work. But, the model provides significant insight into the problems linked with the current design. Microscale surface roughness provides a large electrical leakage path reducing the surface tension gradient, which leads to loss of driving force in comparison to CEW. Further, use of surfactant incorporates a surface tension gradient term, which has not been included in our model. Initial theoretical understanding of the effects of the surfactant is that it inhibits motions.

Even though electrolyte based microactuation of the liquid metal had been successfully demonstrated with limited speed of actuation, doubts about its RF performance encouraged us to develop electrolyte-less driving of liquid metal. Electrolyte-less drive can also perform in high power conditions without any possibility of device failure due to high temperature. Several device structures and substrates were used in fabricating and testing prototypes. Actuation was demonstrated on all the devices with varying actuation speeds.

We performed theoretical investigation to understand the contribution of electrostatic force and surface tension change in the microactuation. A complete model was developed and governing equations were derived. The driving force is derived by representing the system with an electrical equivalent circuit (Figure 2) and solving for energy minimization conditions. Charges at LM droplet interface imply presence of electrowetting (change of contact angle with voltage). We arrive at the same driving force when starting from Lippmann's equation and solving it with the Laplace equation. This implied that electrostatic and the electrowetting effects are the same for our case. In order to achieve droplet motion the actuation force needs to overcome a critical force (stiction) due to contact angle hysteresis. Equating the driving force with the stiction force we obtain the expression for driving voltage (Figure 3).

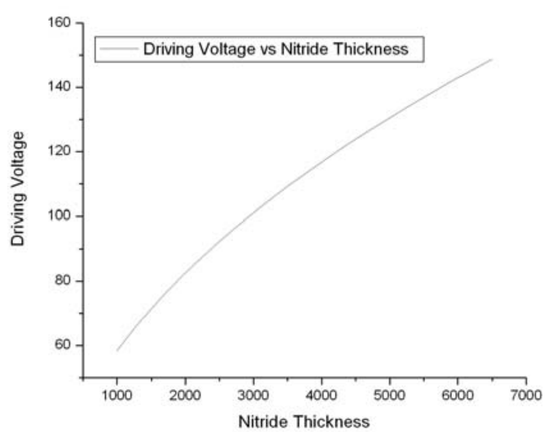


Figure 5. Theoretical driving voltage

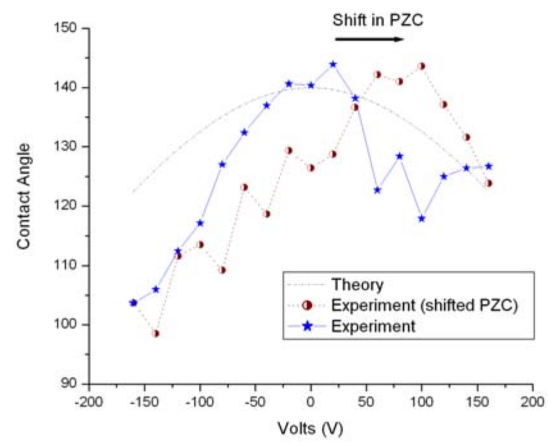


Figure 6. Shift in PZC (experimental)

Initial driving experiments required much higher driving voltages than predicted by the theory. This led us to initiate a series of experiments in order to understand the anomaly. Electrowetting experiments showed a shift in the point of zero charge (PZC) as shown in Figure 4. Dielectric/interface charge trapping was used to explain the shift. It also explained the anomalous shift in driving voltage. We studied the charging of the interfaces and their effect on driving phenomenon. Design rules were developed based on the theoretical understanding and experimental observations. Based on the design rules we developed and demonstrated one-sided driving mechanism.

Task #2: RF Characterization of Liquid-Metal

Without waiting for optimization of the driving mechanism, we decided to perform characterization of the liquid-metal performance for high frequency RF under simulated conditions (i.e. without actuation), as illustrated in Fig 5.

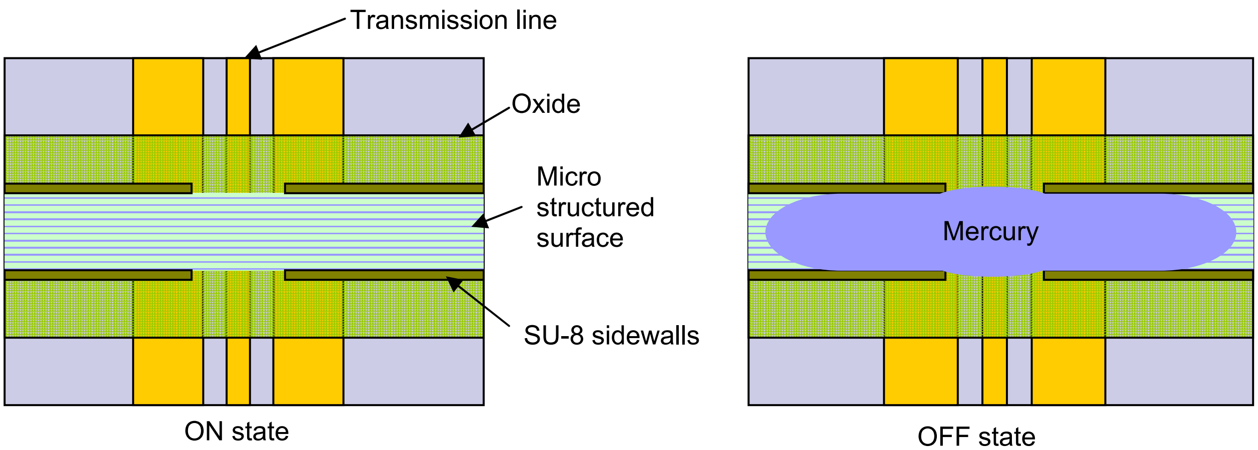


Figure 7. Schematic of the test characterizing liquid metal under high frequency RF

In our experiments mercury was used as a switch element in shunt configuration as illustrated in Figure 5. Better than 25dB isolation was obtained in our experiments upto 40GHz. To simplify experiments switches were designed with long lengths (10mm), which lead to an insertion loss of 1dB. We designed switches with improved assembly techniques to realize shorter switches to achieve the project goal of 0.15dB. To verify our design of liquid metal-based switches we used HFSS simulation software. We first matched our previously obtained experimental data with the simulation results to test feasibility of using the software for liquid metals. Once affirmative results were obtained we expanded our use of the software and simulated new device designs to achieve the project goal of better than 0.15dB insertion loss. High isolation was also achieved during the simulation. Devices were fabricated based on simulated design to verify the loss. Figure 6 shows measured insertion loss and isolation of the designed devices.

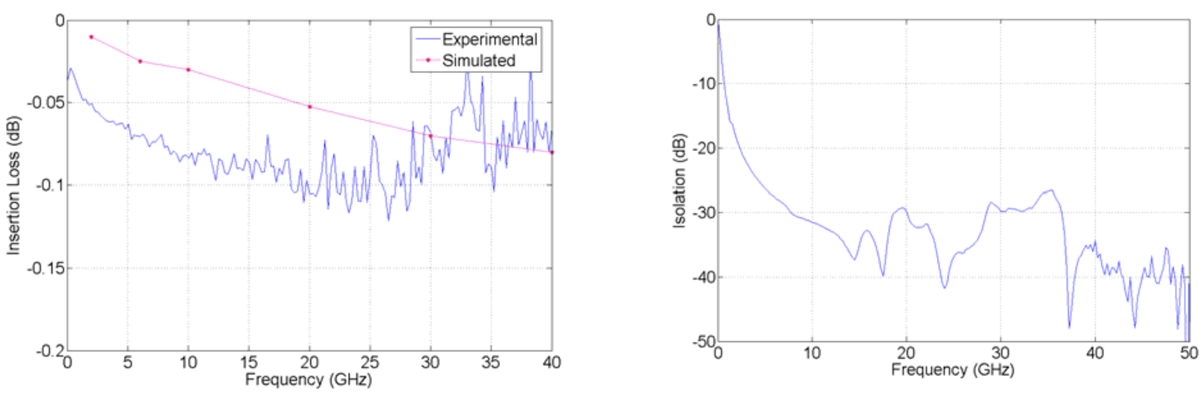


Figure 8. Measured insertion loss and isolation for the devices

D. Summary

We were able to prove the basic microactuation idea at microscale, using microfabricated prototypes. We developed a detailed theory of our actuation mechanism. Various experiments were performed to validate the theory and techniques developed to overcome the interface-charging problem. Based on the theoretical understanding, we designed new devices for integration with microwave circuits and demonstrated actuation speeds better than 3.3 cm/s. Pursuing reduction of hysteresis for achieving high actuation speeds would be a good future topic beyond the current project. In the mean time, characterization of liquid-metal for high RF frequencies was performed experimentally, using a stationary (i.e., not actuated) mercury droplet in a RF electrode pattern designed for this testing purpose. Better than -25dB isolation was provided by the mercury droplet. New devices were designed and simulated using HFSS to significantly lower the insertion loss. Based on the new design devices were fabricated and measured results showed less than 0.15 dB insertion loss.

E. Patents: N/A

F. Publications:

[1] P. Sen and C.-J. Kim, "Electrostatic Fringe-Field Actuation for Liquid-Metal Droplets", *Proc. The 13th Int. Conf. Solid-State Sensors, Actuators and Microsystems (Transducers)*, pp. 705-708, Seoul, Korea, June 2005.

G. Public Presentations: N/A

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